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Abstract

There has been much discussion of fast charging of lithium-ion batteries as a means of extending the practical daily range of electric vehicles making them more competitive with engine-powered conventional vehicles in terms of range and refueling time. In the present study, fast charging tests were performed on cells of three lithium-ion chemistries to determine their characteristics for charging rates up to 6C. The test results showed that the lithium titanate oxide chemistry has a clear advantage over the other chemistries especially compared to the Nickel Cobalt Manganese chemistry for fast charging.

In this paper, the results of extensive testing of 50Ah LTO cells and 24V modules from Altairnano are reported. The modules were instrumented so that the voltage of the individual cells could be tracked as well as three interior temperatures. Cooling of the modules was done via a cooling plate positioned on one end of the module. Life cycle testing of the 24V module is still underway. The cycling involves fast charging at the 4C rate and discharging at C/2. The voltage at the end of the charge corresponds to a state-of-charge of 90 % and the voltage at the end of the discharge corresponds to a state-of-charge of 24 % resulting in the use of 33.3 Ah (66%) from the module. The charging is done at 200A and the discharge at 25A. The charging time is 10 minutes and the discharge time is 80 minutes. The test cycle is meant to mimic the use of the module in a transit bus application with fast charging. To date the module has experienced 285 cycles without any apparent degradation in Ah capacity or voltage response. The maximum measured temperature inside the module stabilized at about 40 deg C without active fan cooling.

Keywords: lithium battery, fast charge, cycle life

1 Introduction

There has been much discussion [1-3] of fast charging of lithium-ion batteries as a means of extending the practical daily range of electric vehicles making them more competitive with engine-powered conventional vehicles in terms of range and refueling time. It has been recognized [4-6] that the lithium titanate oxide (LTO) chemistry is the most capable of fast charging of the various lithium battery chemistries. However, there has been very limited test data available in which the batteries have been fast charged and their response characteristics to fast charging determined. In the study reported in this paper, LTO cells and modules were tested at charge rates up to 8C and their electrical and thermal responses measured. Life cycle testing was also part of the study.

The first part of this paper is concerned with general considerations and requirements for fast charging batteries regardless of their chemistry. Next an approach for determining whether a particular battery appears to be well suited for fast charging is presented and test data are given for fast charging of several lithium battery chemistries. In later sections of the paper, testing of 50 Ah LTO cells and 24V modules from Altairnano is discussed and test data presented for fast charging up to the 6C rate. Special attention is given to the thermal response of the cells and modules to repeated fast charging. Finally, life cycle data are presented for 4C charging and C/2 discharging of the 24V module.

2 General considerations and requirements

2.1 What is meant by fast charging?

The term,"fast charging", is not well defined [1] either in terms of the time/rate of the charging or the fraction of the energy or Ah returned to the battery during the fast charge. Further, it is not stated whether the fast charge is an occasional event or whether the fast charging is done repeatedly on a regular basis as would be the case with a battery-powered transit bus [7] of limited range. In the latter case, thermal/cooling and the effect of fast charging on cycle life are important. The present study was primarily concerned with the case of repeated fast charging.

The most common fast charging time is 10 minutes (6C rate) because that was the time set for fast charging by the California Air Resources Board (CARB) [8] in their early requirements for electric vehicle credits. The energy returned to the battery in the fast charge was required to be sufficient that the additional range of the vehicle after the charge would be at least 95 miles. In most cases, this would mean that the charge would return a large fraction (at least 80-90%) of the energy capacity (kWh) of the battery. In that test, sufficient cooling would be required to maintain the battery temperature below a safe level for a single fast charge.

In a particular application, the fast charging time and fraction of energy returned would be specified to meet the requirements of the user. The charging time is likely to be longer than the 10 minutes set by CARB and in most cases a smaller fraction of energy would be returned to the battery. Charging times of 15-20 minutes (3-4C rate) and energy fractions of 50-75% seem to be practical. If repeated fast charging is needed, then sufficient cooling is necessary to keep the cell/battery temperatures from exceeding 50-55 deg C for long cycle life. In this case, the cooling requirement will be dependent on the discharge rate because the temperature decrease during the discharge must balance the temperature increase during the fast charging if the battery temperatures are to stabilize for the charge/discharge cycles.

2.2 Fast charging power requirements

The current and power for fast charging (nC) is dependent on the cell Ah and the voltage of the battery pack.

$$I_{DC}\,(A) = (Ah)_{cell} \times nC,$$
$$P_{DC}\,kW) = I_{DC} \times (V_{max})_{pack}/1000$$

As indicated in Table 1, the charging currents and power can be high in practice for charging times of 20 minutes or less requiring expensive, high power Level 3 chargers [9].

Table 1: Fast charging power requirements for PHEVs and EVs

nC	**Charging time**	**PHEV battery* 20Ah 7.2 kWh**	**EV battery* 50Ah 18 kWh**
		I_{DC} (A)/P_{DC} (kW)	**I_{DC} (A)/P_{DC} (kW)**
1/3	3 hr.	6.7 / 2.4	16.6 / 6.0
1	1 hr	20 / 7.2	50.0 / 18.0
2	.5 hr	40 / 14.4	100 / 36.0
3	20 min	60 / 21.6	150 / 54.0
4	15 min	80 / 28.8	200 / 72.0
5	12 min	100 / 36.0	250 / 90.0
6	10 min	120 / 43.2	300 / 108
7	8.6 min	140 / 50.4	350 / 126
8	7.5 min	160 / 57.6	400 / 144
12	5 min	240 / 86.4	600 / 216
20	3 min	400 / 144	1000 / 360

* V_{max}= 360V

2.3 General approach to battery charging for all battery chemistries

The most common charging algorithm is constant current to a clamp or maximum battery voltage and current taper at the clamp voltage. For fast charging, the current taper is not usually used because it adds significantly to the charge time and only marginally to the energy returned to the battery. As noted previously, the charge current depends on the Ah rating of the cells and the charge rate nC. The clamp voltage depends on the battery chemistry ($V_{open\ circuit}$) and the number of cells in series in the pack. The temperature limits for charge termination depend on the battery chemistry. Controlling the current near full charge is the key to achieving long cycle life and safe operation of the pack.

The temperature rise of the pack is primarily due to the resistance heating during the fast charge. The heating due to the resistance is I^2R. Additional heating is due to the chemical reactions (TdS) in the battery [10] given by

$$Q = I\,(IR - T[d(V_{open\ circuit})/dT] - Q_{loss}/I), \quad I>0 \text{ for charging}$$

For fast charging, Q is positive (heating) for all battery chemistries, but for discharging Q can be positive or negative depending on the current and battery chemistry (dV_{oc}/dT).

3 Fast charging characteristics of various lithium battery chemistries

The cell resistance R_{cell} is dependent on the Ah of the cell and the battery design, but in general it is reasonable to assume that

$$R_{cell} \times Ah = \text{constant} = C_R$$

for a particular technology. Hence the major heating during fast charging is given by

$$P_{heating}/\text{cell} = I_{DC}^2\, C_R/Ah = C_R\,(Ah)\,(nC)^2$$

It is of interest to determine the ratio of the heating energy during charging to the energy stored in the cell or pack.

$$E_{heating}/E_{stored} = [P_{heating}/\text{cell} \times 1/nC] / (V_{cell}\,Ah) = C_R\,(nC)/V_{cell}$$

The efficiency of the charge is then given by

$$\text{Efficiency} = 1 - C_R\,(nC)/V_{cell}$$

The cells and battery chemistry most suitable for fast charging would be those with high efficiency.

A summary of the performance and fast charging characteristics of the cells tested at UC Davis [11, 12] is given in Table 2. The charging efficiencies for fast charging vary over a wide range depending primarily on the resistance of the cell. Some of the lithium-ion cells have high charging efficiencies and thus would be good candidates for fast charging.

In addition to high charging efficiency, another characteristic which is important for fast charging is the fraction of total Ah capacity of the cell that has been returned when the charge voltage reaches the clamp voltage. This means that it is not necessary to taper the current to reach near full charge. As shown in Table 3, the various battery chemistries differ significantly with respect to this characteristic. Note that for the iron phosphate and lithium titanate oxide chemistries only a small fraction of the charge is returned to the cell after the clamp voltage was reached.

Table 2: Summary of the performance and fast charge characteristics of batteries of various chemistries

Battery Developer/ Cell type	Electrode chemistry	Voltage range	Ah	Resist. mOhm	RxAh	Wh/kg	$E_{heating}/E_{store}$ nC=4
Enerdel HEV	Graphite / Ni MnO2	4.1-2.5	15	1.4	.021	115	.022
Enerdel EV/PHEV	Graphite / Ni MnO2	4.1-2.5	15	2.7	.041	127	.047
Kokam prismatic	Graphite / NiCoMnO2	4.1-3.2	30	1.5	.045	140	.05
Saft Cylind.	Graphite / NiCoAl	4.0-2.5	6.5	3.2	.021	63	.025
GAIA Cylind.	Graphite / NiCoMnO2	4.1-2.5	40 7	.48 3.6	.019 .025	96 78	.022 .029
A123 Cylind.	Graphite / Iron Phosph.	3.6-2.0	2.2	12	.026	90	.032
Altairnano prismatic	LiTiO / NiMnO2	2.8-1.5	11 3.8	2.2 1.15	.024 .0044	70 35	.04 .007
Altairnano prismatic	LiTiO / NiMnO2	2.8-1.5	50	.7	.035	70	.058
Quallion Cylind.	Graphite / NiCo	4.2-2.7	1.8	60	.108	144	.12
EIG prismatic	Graphite / NiCoMnO2	4.2-3.0	20	3.1	.062	165	.071
EIG prismatic	Graphite/Iron Phosph.	3.65-2.0	15	2.5	.0375	113	.045
Panasonic EV prismatic	Ni Metal hydride	7.2-5.4	6.5	11.4	.013	46	.045
Hawker prismatic	Lead-acid	12-10.5	13	15	.033	29	.066

Table 3: Summary of the 1C charging characteristics of batteries of various chemistries

Battery chemistry	Capacity Ah	Clamp voltage V	Charge current A	Time (min.) to clamp/Ah	Time (min.) to cut-off/Ah
NiCoMnO2	20	4.2	20	52/17.3	80/19.6
FePhosphate	15	3.65	15	60/15.2	64/15.4
LiTitanateOx	11	2.8	11	65/11.9	66/11.9
Lead-acid (12V)	38	14.7	25	81/33.9	
			45	45/34	
			65	26/29	

Table 4: Test data for fast charging for lithium-ion chemistries

EIG iron phosphate 15 Ah cell							
Charge Current (A)	Time to Cutoff (secs)	Taper Time (secs)	Charge to Cutoff (Amp-hrs)	Total Charge (Amp-hrs)	Discharge (Amp-hrs)	Initial Temp (°C)	Temp Change (°C)
15	3630	210	15.2	15.4	15.50	22.5	0
30	1770	210	14.7	15.4	15.45	22.5	1.5
45	1140	199	14.2	15.4	15.38	22.5	3
60	840	172	13.9	15.3	15.30	23.5	4.5
75	630	184	13.1	15.3	15.29	25.5	5.5
90	480	219	11.9	15.2	15.17	23	7
120	240	316	7.9	15.2	15.16	25	9
No Taper							
60	780.4		13.6		12.99		
90	464.8		11.6		11.60		
Altairnano titanate oxide 11 Ah cell							
Charge Current (A)	Time to Cutoff (secs)	Taper Time (secs)	Charge to Cutoff (Amp-hrs	Charge (Amp-hrs)	Discharge (Amp-hrs)	Initial Temp (°C)	Temp Change (°C)
11	3920	81	11.9	12.0	12.00	22.5	0
22	1950	68.5	11.9	12.0	12.00	22	0.5
33	1300	57.7	11.9	12.0	12.00	22.5	1.5
44	970	59.2	11.8	12.0	12.01	23	2.5
55	760	74.8	11.6	12.0	11.97	21.5	4
66	620	83	11.3	12.0	11.97	22.5	4.5
88	440	103.1	10.7	12.0	11.97	24	6.5

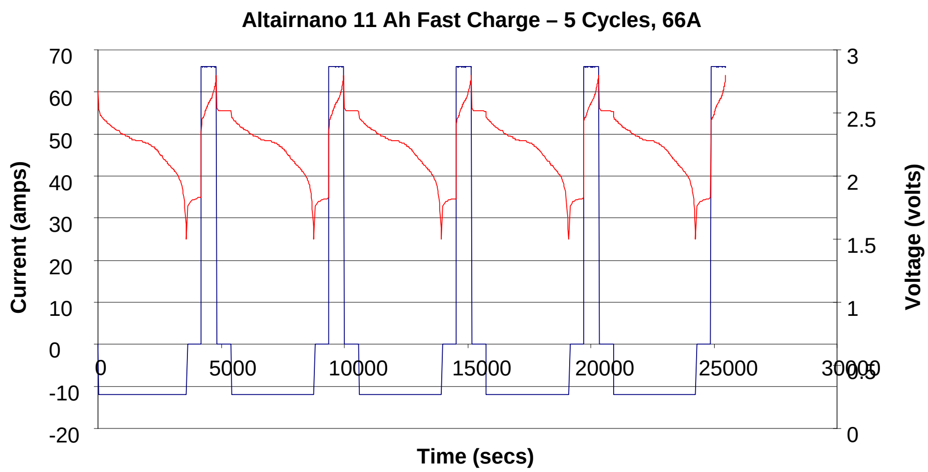


Figure 1: Repeated fast charging cycles of the 11Ah lithium titanate oxide cell (6C charge and 1C discharge)

Test data for the fast charging of iron phosphate and lithium titanate oxide cells are given in Table 4. The cells are charged at 1C to 8C rates and discharged at the 1C rate. The clamp voltage for the iron phosphate cell was 3.65V and that of the lithium titanate oxide cell was 2.8V. The current was tapered at the end of charge in all the tests. As shown in Table 4, both cells exhibited good fast charging capability (up to 8C). As would be expected, the temperature rise during the charge increased with increasing charge current (nC). As shown in Figure 1, subsequent testing involving repeated fast charges and 1C discharges indicated the maximum temperature at the end of the fast charge stabilized and repeated fast charging could be done with the 11 Ah lithium titanate oxide cell without active cooling (no fan –only natural convection to the lab).

Tests were performed on three lithium-ion battery chemistries to determine the fraction of the Ah capacity that could be returned without current taper. The results of the testing are summarized in Table 5. The lithium titanate oxide chemistry has a clear advantage over the other chemistries especially compared to the Nickel Cobalt Manganese chemistry for fast charging.

Table 5: Maximum charge capacity without taper for fast charging of lithium-ion batteries of various chemistries

Charge rate	Percent Ah to clamp voltage		
	Nickel Cobalt Manganese	Iron Phosphate	Lithium Titanate
3C	81%	92%	99%
4C	76%	90%	98%
5C	72%	85%	96%
6C	----	78%	94%

4 Fast charging tests of 50Ah lithium titanate oxide cells and modules

4.1 Cell testing

The discharge characteristics of the 50Ah lithium titanate oxide cell from Altairnano used in the fast charging tests are given in Table 6. The cell had a resistance of about .9 mOhm resulting in a C_R value of .045, which is typical for lithium cells, but not particularly low for an LTO cell (see Table 2). The Ah capacity of the cell varied little with discharge rate up to 6C. Based on the test results in Section 3, it is reasonable to expect that the 50Ah cell would have good fast charging characteristics.

Table 6 : Characteristics of the Altairnano 50Ah cell

Constant current discharges (2.8-1.5V)

Current A	nC	Time sec	Ah
50	.96	3773	52.4
100	1.95	1847	51.3
200	4.0	904	50.2
300	6.1	588	49.0

Constant power discharge (2.8-1.5V)

Power W	W/kg	Time sec	nC	Wh	Wh/kg
100	62	3977	.9	111	69
200	125	1943	1.85	108	67
300	188	1244	2.9	102	64
400	250	849	4.2	94	59
500	313	636	5.66	88	55
600	375	516	7.0	86	54

weight: 1.6 kg

Summary of the cell power characteristics

SOC	V_{oc}	R (mOhm)	$(W/kg)_{90\%\ eff.}$	$(W/kg)_{80\%\ eff.}$
1.0	2.7	.9	455	811
.9	2.45	.8	422	751
.8	2.40	.8	405	721
.7	2.36	.8	392	698
.6	2.34	.9	343	609
.5	2.33	.9	339	604
.4	2.32	.95	319	568
.3	2.27	1.15	252	448
.2	2.2	1.25	218	388
.1	2.14	1.35	191	339

Figure 2: Testing of the 50 Ah lithium titanate oxide cell

Fast charging tests of the 50Ah cell were performed at charging rates up to 6C. Photographs of the cell and laboratory setup are shown in Figure 2. Initial testing of the cell was done with the cell insulated as shown in the figure. The outer surface of the cell was instrumented with an array of thermocouples to track the temperature changes during the charge/discharge cycles. The cycles consisted of nC charging and C/2 discharges with rest periods (5 minute) at the end of the charge and discharge periods. There was no current taper to complete the charge at 2.8V. The charge/discharge cycles were repeated to determine whether the temperatures would stabilize at less than 50 deg C. The initial tests were run with the cell in an insulating blanket as shown in Figure 2. When it was found that the temperatures for charging at 3C exceeded 60 deg C after two charge/discharge cycles (see Figure 3) further testing of the cell was done with the cell open to the ambient lab temperature (see Figure 4). The thermal response of the cell to charging at 6C in free air is shown in Figure 5. As shown in the Figures 3-5, there is a temperature variation of greater than 10 deg C over the surface of the cell in all the tests with the temperature highest at the top of the cell near the tabs. The testing indicated that for fast charging the 50 Ah cell as is done in the transit bus application by Proterra [x] some cooling of the cell will be necessary, but the level of cooling required is likely to be relatively small, because in the lab tests of the cell, free convection cooling was adequate to maintain stable temperatures to repeated fast charging with a C/2 discharge up to 6C charging. As indicated by the voltage plots in Figures 3-5, the Ah capacity of the cell was stable for repeated cycles.

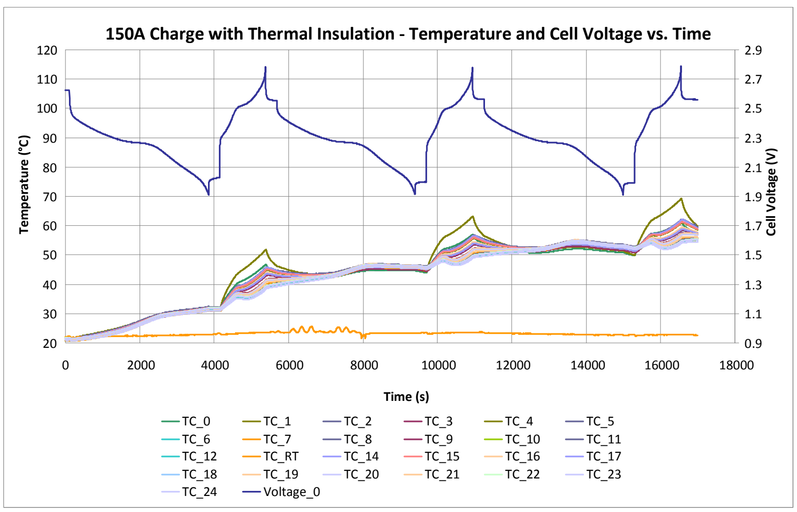


Figure 3: Thermal response of the 50Ah cell to repeat charging at 3C (150A) with the insulating blanket

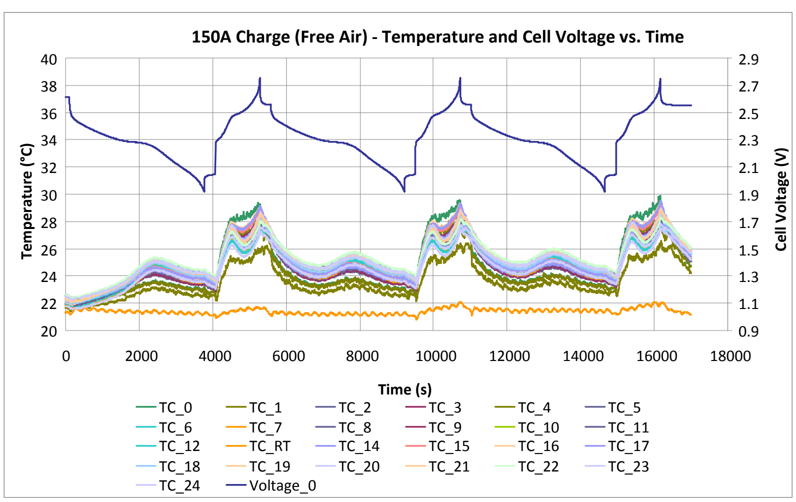


Figure 4: Thermal response of the 50Ah cell to repeat charging at 3C (150A) open to free air

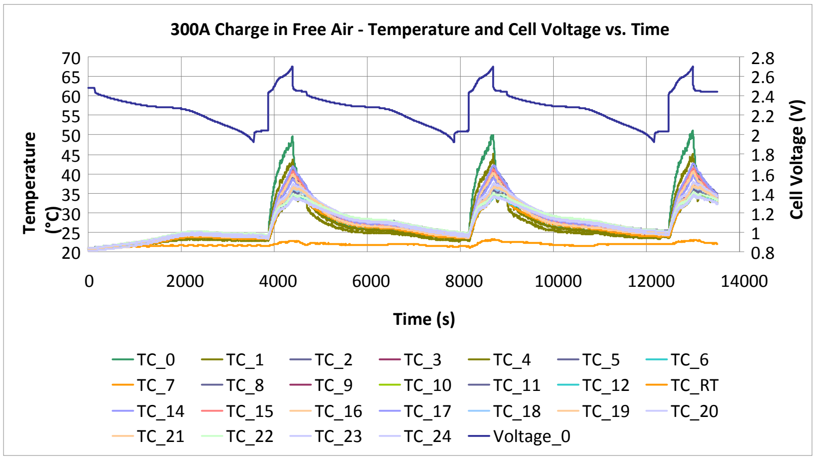


Figure 5: Thermal response of the 50Ah cell to repeat charging at 6C (300A) open to free air

4.2 Module testing

4.2.1 Module characteristics

The modules consisted of ten 50 Ah cells connected in series. The nominal voltage of the module is 24V with a maximum clamp voltage for charging of 28V. The module characteristics are summarized in Table 7. The energy density of the module for a 1C discharge is 49 Wh/kg, 85 Wh/L. The corresponding cell values are 70 Wh/kg, 128 Wh/L. The modules were instrumented such that the voltages of the individual cells could be recorded and the cell resistances calculated. The cell resistances for a typical module are given in Table 8 for both discharge and charge currents from 100-300A. The standard deviation of the cell-to-cell variability of the resistance is about 9%. The cell and module resistances do not vary significantly with current and in all cases, the module resistances are close to the sum of the resistances of the 10 cells. The Ah capacity of the modules for charge rates up to 6C are also given in Table 8. As expected for the lithium titanate oxide battery, the Ah capacity of the module varies only slightly with charge rate even without current tapering.

Table 7: Characteristics of the 24V Lithium Titanate Oxide Module

Module configuration	Ten 50Ah cells in series
Weight (kg)	23.2 module, 16 cells alone
Volume (L)	13.25 module, 8.9 cells alone
Ah capacity	50.5 at 50A, 44.2 at 200A
Energy density (Wh/kg)	70.6 at 1C, 66.4 at 2C
Resistance (mOhm)	7.0
Pulse power (W, W/kg)	6.7 kW, 420 W/kg cells alone, 90% effic.
Fast charging capability	Up to 6C with 96% of rated Ah

4.2.2 Fast charging characteristics of the modules

The fast charging characteristics of modules using the 50Ah cells were also studied. The modules were charged at up to the 6C rate with air blowing over them from a fan as shown in Figure 6. As shown in the figure, the cooling backplate of the module was instrumented with thermocouples. There were also three thermistors mounted internal to the module. The modules were charged at the nC rates and discharged at the C/2 rate. Each test consisted of four repeated charge/discharge cycles.

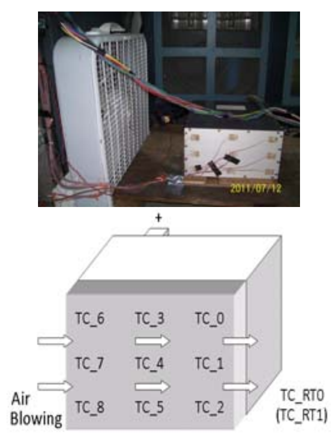


Figure 6: Test setup for the fast charging of the 24V module

The temperatures on the cooling backplate and in the interior of the module were recorded during the test cycles. The voltage/current traces and the temperature distributions for the 6C charging cycles are shown in Figure 7 and 8.

Table 8: Cell- to-cell variation of resistance in the 24V module

50Ah module	R (mOhm)						
	Pulse Current						
cell #	-300A	-200A	-100A	100A	200A	300A	ave R
0	0.598	0.589	0.584	0.583	0.576	0.571	0.584
1	0.675	0.669	0.661	0.656	0.651	0.642	0.659
2	0.802	0.796	0.786	0.778	0.770	0.758	0.7814
3	0.746	0.737	0.733	0.726	0.716	0.704	0.727
4	0.701	0.694	0.692	0.686	0.676	0.667	0.686
5	0.740	0.732	0.727	0.717	0.711	0.699	0.721
6	0.713	0.706	0.699	0.695	0.687	0.677	0.6961
7	0.713	0.704	0.700	0.695	0.688	0.678	0.696
8	0.787	0.777	0.769	0.770	0.752	0.737	0.765
9	0.633	0.623	0.6113	0.606	0.608	0.598	0.613
Average	0.711	0.703	0.696	0.691	0.684	0.673	0.693
St Dev	0.064	0.064	0.064	0.063	0.060	0.058	0.062
module R	7.109	7.201	6.840	6.891	7.016	6.739	(mOhm)

Charge Current	50A	150A	200A	250A	300A	
module Ah	50.5	50.4	50.1(49.9)	49.5(49.3)	48.7(48.3)	(fan cooling)

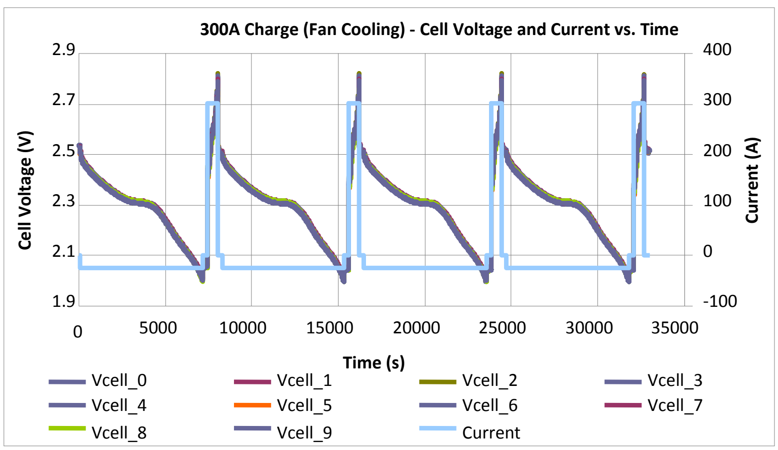


Figure 7: Voltage and current traces for repeated 6C, C/2 cycles of the 24V module

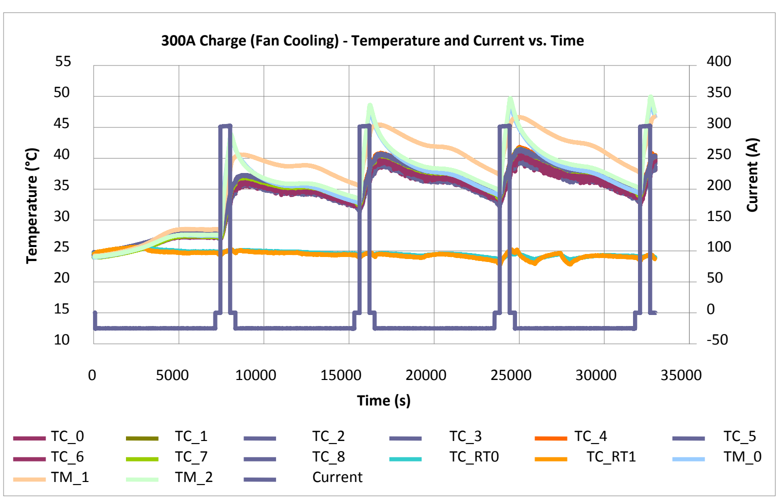


Figure 8: The temperature distributions for the 24V module during repeated 6C, C/2 cycles

The data shown in Figures 7 and 8 indicate that at the end of four cycles the voltage and temperature distributions have stabilized for the 6C fast charge test. The maximum interior temperature reached is 50 deg C with a corresponding maximum temperature of 40 deg C on the backplate. A summary of the estimated average cooling to/from the module during the charge/discharge cycle is given in Table 9.

Table 9: Estimated average cooling of the module during a 6C, C/2 cycle

Max. temp. at end of charge	50C
Min. temp. at end of discharge	33C
Average cooling during charging	120W/module
Average cooling during discharging	48W/module
Cooling plate temperatures	33-40C

The data shown indicate that the 24 module can be repeatedly fast charged at rates up to 6C when the discharge rate between the fast charges is at least C/2. There is need for cooling, but the needed cooling is not large being in the range of 100-150W during the charging. At lower charge rated like 4C, the needed cooling would be less.

4.2.3 Life cycle testing of the module with fast charging at 4C

Life cycle testing of the 24V module is underway. The cycling involves fast charging at the 4C rate and discharging at C/2. The voltage at the end of the charge (26.45V) corresponds to a state-of-charge of 90 % and the voltage at the end of the discharge (21.72V) corresponds to a state-of-charge of 24 % resulting in the use of 33.3 Ah (66%) from the module. The charging is done at 200A and the discharge at 25A. The charging time is 10 minutes and the discharge time is 80 minutes. This test cycle is meant to mimic the use of the module in a transit bus application with fast charging.

The life cycle testing was done in blocks of 30 cycles which takes about 2 days per block. The tests were run without the cooling fan. Samples of the life cycle results are shown in Figures 9 and 10. Figure 9 shows the voltage and maximum temperature interior to the module. As indicated the maximum temperature stabilized at about 40 deg C without active fan cooling.

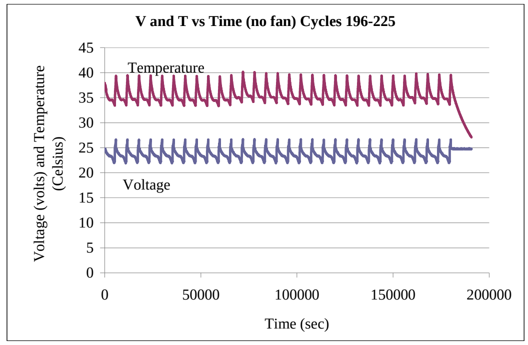
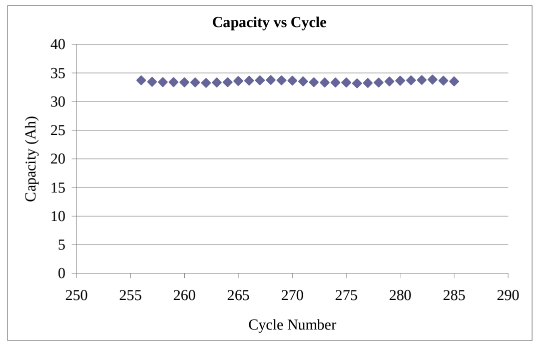


Figure 9: Voltage and maximum interior temperature data for the lifecycle testing of the 24V module with fast charging



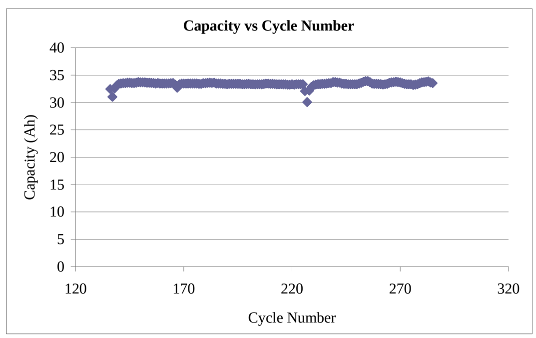


Figure 10: Life cycle data (cell Ah capacity) for the 24V module for 285 cycles with fast charging

The tests results to date (285 cycles) indicate that the module shows no degradation in cycle Ah capacity and that the voltage and temperature characteristics on the test cycle are very stable with a high degree of repeatability. The only small variations in the test data occur when the life cycle testing is resumed after stoppage due to the need to use the battery tester for other research.

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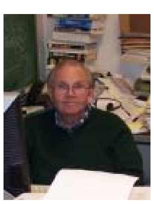

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